

EVIDENCE FOR THE WHITE DWARF NATURE OF MIRA B

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ABSTRACT

The nature of the accreting companion to Mira — the prototypical pulsating asymptotic giant branch star — has been a matter of debate for more than 25 years. Here we use a quantitative analysis of the rapid optical brightness variations from this companion, Mira B, which we observed with the Nickel telescope at Lick Observatory, to show that it is a white dwarf (WD). The amplitude of aperiodic optical variations on time scales of minutes to tens of minutes (≈ 0.2 mag) is consistent with that of accreting WDs in cataclysmic variables on these same time scales. It is significantly greater than that expected from an accreting main-sequence star. With Mira B identified as a WD, its ultraviolet (UV) and optical luminosities, along with constraints on the WD effective temperature from the UV, indicate that it accretes at $\sim 10^{-10} M_{\odot} \text{ yr}^{-1}$. We do not find any evidence that the accretion rate is higher than predicted by Bondi-Hoyle theory. The accretion rate is high enough, however, to explain the weak X-ray emission, since the accretion-disk boundary layer around a low-mass WD accreting at this rate is likely to be optically thick and therefore to emit primarily in the far or extreme UV. Furthermore, the finding that Mira B is a WD means that it has experienced, and will continue to experience nova explosions, roughly every 10^6 years. It also highlights the similarity between Mira AB and other jet-producing symbiotic binaries such as R Aquarii, CH Cygni, and MWC 560, and therefore raises the possibility that Mira B launched the recently discovered bipolar streams from this system.

Subject headings: stars: individual (HD 14386, VZ Ceti) — binaries: symbiotic — novae, cataclysmic variables — accretion, accretion disks — white dwarfs

1. INTRODUCTION

Variations in the strength of emission from the accretion region around a compact object can reveal fundamental properties of the compact object and its accretion structure. For example, the frequencies associated with features in the power density spectra (PDS) of these brightness variations are linked to physical time scales at different locations in the accretion disk (e.g., Mauche 2002; Warner 2004; Done, Gierliński, & Kubota 2007). Such PDS features include quasi-periodic oscillations, “breaks” where the slope of the PDS changes, and broadband components that can be fitted with Lorentzian functions (Psaltis, Belloni, & van der Klis 1999). Empirically, the locations of these features depend on the type of object; in X-ray binaries, the highest frequency at which significant variability exists is greater for neutron star than black-hole accretors (Sunyaev & Revnivtsev 2000), consistent with the higher Keplerian frequency at the inner edge of the accretion disk around a neutron star. Even an apparently featureless PDS may hold the imprint of the underlying accreting object, as is evidenced by the correlation between the normalization of the PDS at a particular frequency and the mass of the black hole in active galaxies compared to X-ray binaries (Nikolajuk, Papadakis, & Czerny 2004; Gierliński, Nikolajuk, & Czerny 2008).

An important case where accretion-related variations can reveal the nature of an accreting object is the wide, interacting binary-star system Mira AB (*o* Ceti). Mira AB is a ‘symbiotic-like’ or ‘weakly symbiotic’ system at a distance of 107 pc (Knapp et al. 2003). Ac-

cording to the preliminary orbit of Prieur et al. (2002), the orbital period is 497.9 years, and the inclination is 112.0° (i.e., we see the binary nearly edge-on). The donor star is the prototype of the Mira-type class of pulsating AGB stars, with a pulsation period of 332 days (Hoffleit 1997). A more compact companion, whose nature has been controversial, accretes from the wind of the AGB star. Although most indicators suggest that the accretor is a WD (e.g., Warner 1972; Reimers & Cassatella 1985), several authors have argued that the low X-ray luminosity implies it is a main-sequence (MS) star (Jura & Helfand 1984; Kastner & Soker 2004). Determining whether Mira B is a WD or a MS star is imperative because its nature and evolutionary status impact our understanding of: 1) the efficiency of wind-fed accretion; 2) mass transfer through disks with sizes of $\sim 10^{13}$ cm; 3) X-ray emission from symbiotic stars; and 4) the generation of the bipolar structure in planetary nebulae (PNe).

Because Mira AB is spatially resolved in the optical, X-ray, and radio (Karovska et al. 1997, 2005; Matthews & Karovska 2006), it is an excellent place to investigate the accretion of a stellar wind from a detached companion. Roche lobe overflow is thermally unstable when the donor star in a binary is an evolved giant with a mass in excess of $5M/6$ (where M is the mass of the accretor; Webbink, Rappaport, & Savonije 1983). Hence symbiotic binaries, which typically have low-mass accretors (Mikołajewska 2003), tend to transfer material via gravitational capture of the red-giant wind. In Mira AB, X-ray observations revealed a

bridge of material between the two stars (Karovska et al. 2005) that likely arises from the gravitational effects, as the wind speed (6 km s^{-1} ; Knapp & Morris 1985) is of the same order as the stellar velocities. Mira may thus be the first clear example of a new mode of mass transfer — dubbed ‘wind Roche lobe overflow’ (Mohamed & Podsiadlowski 2007) or ‘gravitational focusing’ (de Val-Borro, Karovska, & Sasselov 2009) — that lies somewhere between standard Roche-lobe overflow and Bondi-Hoyle accretion. This type of mass transfer may occur in those wide binaries that ultimately explode as type Ia supernovae (SNIa; e.g., Patat et al. 2007; Simon et al. 2009; Blondin et al. 2009), with the yield from this channel of SNIa production depending on the efficiency of the mass transfer from the RG to the WD. Since the inferred accretion rate onto Mira B ($\dot{M} = LR/GM$, where L is the luminosity due to accretion, R is the radius of the accretor, and G is the gravitational constant) differs by almost two orders of magnitude depending upon whether Mira B is a WD or a MS star, determining the nature of Mira B is critical for estimating \dot{M} and the ability of this channel to produce a SNIa.

Mira AB will also test the hypothesis that the shapes of PNe are the result of interactions between a star in its final stages of evolution and a binary companion (De Marco 2009). Observations indicate that pre-PNe commonly have bipolar morphologies and jets (e.g., Bujarrabal et al. 2001; Sahai et al. 2007), and most models for producing these structures require a binary companion (e.g., De Marco 2009; Huggins, Maun, & Wirth 2009, and references therein). Miszalski et al. (2009), however, estimated that only 10–20% of PNe contain binary central stars with separations small enough for the binary to have experienced a phase of common-envelope evolution, and Huggins, Maun, & Wirth (2009) argued that the roundness of the majority of the halos of pre-PNe indicates that any binary companions in these systems must either be quite distant (as in Mira) or have very low masses. Mira A is near its evolutionary end state, it has a distant binary companion, and recent ultraviolet (UV) images from the *GALEX* satellite revealed bipolar “streams” of knots to the north and south (Martin et al. 2007). Therefore, resolution of the issue of the nature of the companion would clear the path for models of Mira AB to confront questions such as how wide binaries generate bipolar structure in PNe, which stellar component launches the bipolar outflows, and when asymmetry first appears.

In this paper, we use fast *B*-band photometry to show that Mira B is a WD. We describe our rapid photometric observations in §2, and the resulting light curves and power density spectra in §3. In §4, we explain how the amplitude of the optical variations on time scales of minutes reveal Mira B to be a WD. We also estimate a characteristic accretion rate onto Mira B and reinterpret the X-ray emission. We summarize our conclusions and explore several implications in §5.

2. OBSERVATIONS AND DATA REDUCTION

As part of a photometric survey of 35 symbiotic stars (see Sokoloski, Bildsten, & Ho 2001, hereafter SBH), we observed Mira AB with the 1-m Nickel telescope at UCO/Lick Observatory on Mt. Hamilton, near San Jose,

TABLE 1
LOG OF MIRA AB OBSERVATIONS

Date, U.T.	Obs. Start (MJD)	Duration (hr)	t_e (s)	Δt (s)	Num. Pts
1997 Sep 2	50693.350	3.6	25.0	46.996	256
1997 Nov 3	50755.410	1.6	50.0	70.0	81
1998 Aug 19	51044.482	1.0	18.0	38.990	97
1998 Aug 20	51045.381	3.5	30.0	49.988	248
1998 Sep 17	51073.352	4.6	25.0	46.0	355

NOTE. — Obs. Start is the start time for a given observation. Duration is the length of the observation. Columns 4 and 5 lists the exposure time and the time between exposure starts as t_e and Δt , respectively.

CA, on 5 nights between 1997 September and 1998 September. Table 1 contains a log of the observations, each of which consisted of a series of exposures with an unthinned, 2048×2048 Loral CCD (referred to at Lick Observatory as ‘CCD 2’) that had $15\text{-}\mu\text{m}$ pixels and a $6'.3 \times 6'.3$ field of view. We chose exposure times, t_e , of 18 to 50 s to maximize the signal-to-noise ratio (S/N) while avoiding saturation of the program star or the one bright comparison star in the field of view (HD 14411). Keeping the exposure times at or above 18 s also kept the observing efficiency ($t_e/\Delta t$, where Δt is the time between observation starts) from dropping much below $\sim 50\%$ and minimized scintillation noise, which can dominate the error at very short exposure times (SBH). Including chip pre-processing and readout times of between 20 and 22 seconds, Δt ranged from 39 to 70 seconds. To obtain evenly spaced data points within a given observation, and thereby produce data that were compatible with standard fast Fourier transform (FFT) routines, we employed a timing system developed especially for this project by W. Deitch (UCO/Lick). The resulting light curves spanned from 1.1 to 4.6 hours. To minimize the contribution of the red giant while still obtaining adequate flux from the bluer hot component to generate a high S/N on time scales of minutes, we used a Johnson *B* filter and observed only near the minima of the 332-day Mira pulse period, as displayed in Figure 1.

For each observation, we reduced the CCD images using standard techniques and performed aperture photometry, as described in SBH. For each image, our reduction included subtracting the electronics zero point and bias pattern and dividing by an average of multiple images of the sky, using IDL software based upon IRAF routines (see Gilliland 1992; Massey 1997). We produced differential light curves with respect to either the one bright comparison star in the field or a weighted, ensemble average of 2 – 4 comparison stars (depending upon whether the additional comparison stars improved the S/N enough to warrant the additional lost points due to cosmic rays). We estimated the background for each star from an annulus around that star. We omitted data points contaminated by radiation events (‘cosmic rays’), points with extremely high background, and data taken during exceptionally poor weather conditions. None of the comparison stars showed any evidence for intra-night variability.

3. ANALYSIS AND RESULTS

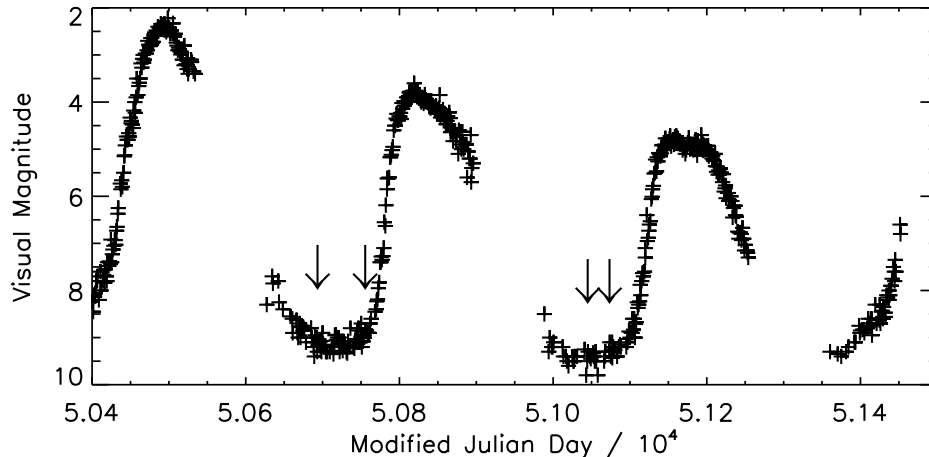


FIG. 1.— Long term visual light curve, from 1996 to 1999, from the American Association of Variable Star Observers (AAVSO), with the dates of our high-time-resolution *B*-band observations marked with arrows. Our observations all occurred near a photometric minimum of the pulsating red giant. Since we performed our third and fourth observations on subsequent nights (1998 August 19 and 20), they appear as a single arrow (the third from the left).

TABLE 2
OPTICAL VARIABILITY OF MIRA AB

Date (U.T.)	s_{exp} (mmag)	s^a (mmag)	Powerlaw Index	Freq Range (mHz)	χ^2_ν
1997 Sep 2	2.7	50.9	-1.8 ± 0.2	0.08 – 3.6	0.8
1997 Nov 3	2.6	37.9	-2.4 ± 0.3	0.2 – 3.4	0.8
1998 Aug 19	2.6	29.3	-2.1 ± 0.2	0.3 – 9.3	0.7
1998 Aug 20	2.3	55.3	-2.0 ± 0.1	0.08 – 5.5	0.9
1998 Sep 17	2.5	28.7	-1.9 ± 0.1	0.06 – 10.8	0.9

^a The measured rms variation, s , includes variations at all frequencies to which a given observation was sensitive; the range of frequencies sampled for each observation is approximately equal to the range over which we fitted the powerlaw model, shown in column 5.

Rapid aperiodic variability, like the variability from cataclysmic variables that is often termed ‘flickering’ (CVs; e.g., Warner 1995; Bruch 2000), is evident on all 5 nights. Figure 2 shows the differential light curves from the 5 observations. On each night, the measured root mean square (rms) variation, s , exceeded the rms variation expected from the known errors, s_{exp} , by more than an order of magnitude. Table 2 lists s and s_{exp} (the estimation of which is discussed in detail in SBH) for each observation. Figure 2 demonstrates that the *B*-band flux can change by more than 5% (≈ 50 mmag) in less than 5 minutes and more than 25% (≈ 0.25 mag) in less than 2 hours. Taking into account the non-variable light from the red giant, which contributes $\approx 50\%$ of the flux at *B*-band (since Mira A and B had similar brightness in the *HST* F501N filter when Mira A was near pulse minimum in 1995; Karovska et al. 1997), these rapid fluctuations correspond to variations of approximately 10 – 50% in the *B*-band light from Mira B. In summary, correcting for the contribution from the red giant, the *B*-band flux from Mira B varied as fast as a few per cent (or tens of mmag) per minute, and by order unity in tens of minutes, as exhibited in the light curve from 1998 August 20 (Figure 3).

The PDS of all 5 light curves reveal broadband power with a powerlaw shape — $P_\nu \propto \nu^\alpha$ (where P_ν is the

power density and ν is the frequency) — between approximately 0.1 and 10 mHz (see Table 2). Since our data points were evenly spaced, we used the IDL routine *fft* to compute the PDS. We normalized the PDS to the variance of the light curves using the Miyamoto normalization (Miyamoto et al. 1991), in which the square root of the integrated power between two frequencies is equal to the fractional rms variation between those two frequencies. For PDS with a powerlaw index $\alpha = -2$, the square root of the power at a given frequency equals the fractional rms variation summed over all frequencies above that frequency. Figure 4 shows the PDS corresponding to the light curves in Figure 2. Table 2 lists the powerlaw indices for each observation; they ranged from -1.8 to -2.4 . The weighted average of the 5 powerlaw indices is $\alpha = -1.969 \pm 0.004$. Since this value is very close to $\alpha = -2$, we refer to the stochastic variations from Mira as *red noise*.

Extrapolating the PDS where necessary using a powerlaw index of $\alpha = -2$, and taking into account the constant light from the red giant, we find that the average rms variation from Mira B between 0.1 and 10 mHz is approximately 9%. We derived this value from a measured rms variation for the total *B*-band light in this same frequency range of 4.5%, since emission from the red giant, which does not vary at these frequencies, constitutes approximately half of the *B*-band flux. Thus, the *B*-band rms variation from Mira B is at least twice the rms variation of the total *B*-band light. In the restricted frequency range of 1 – 10 mHz, which is useful for comparison with published rms variations in this frequency range for CVs, the average rms variation from Mira B is 3% (correcting a measured rms variation of 1.5% in this frequency range for the contribution from the red giant).

We did not find any evidence for coherent, periodic variations on time scales of minutes to hours in the optical brightness of Mira B. Taking the broadband power into account (as discussed in the Appendix of Sokoloski & Kenyon 2003), no peaks in the PDS rose significantly above the level of the red noise.

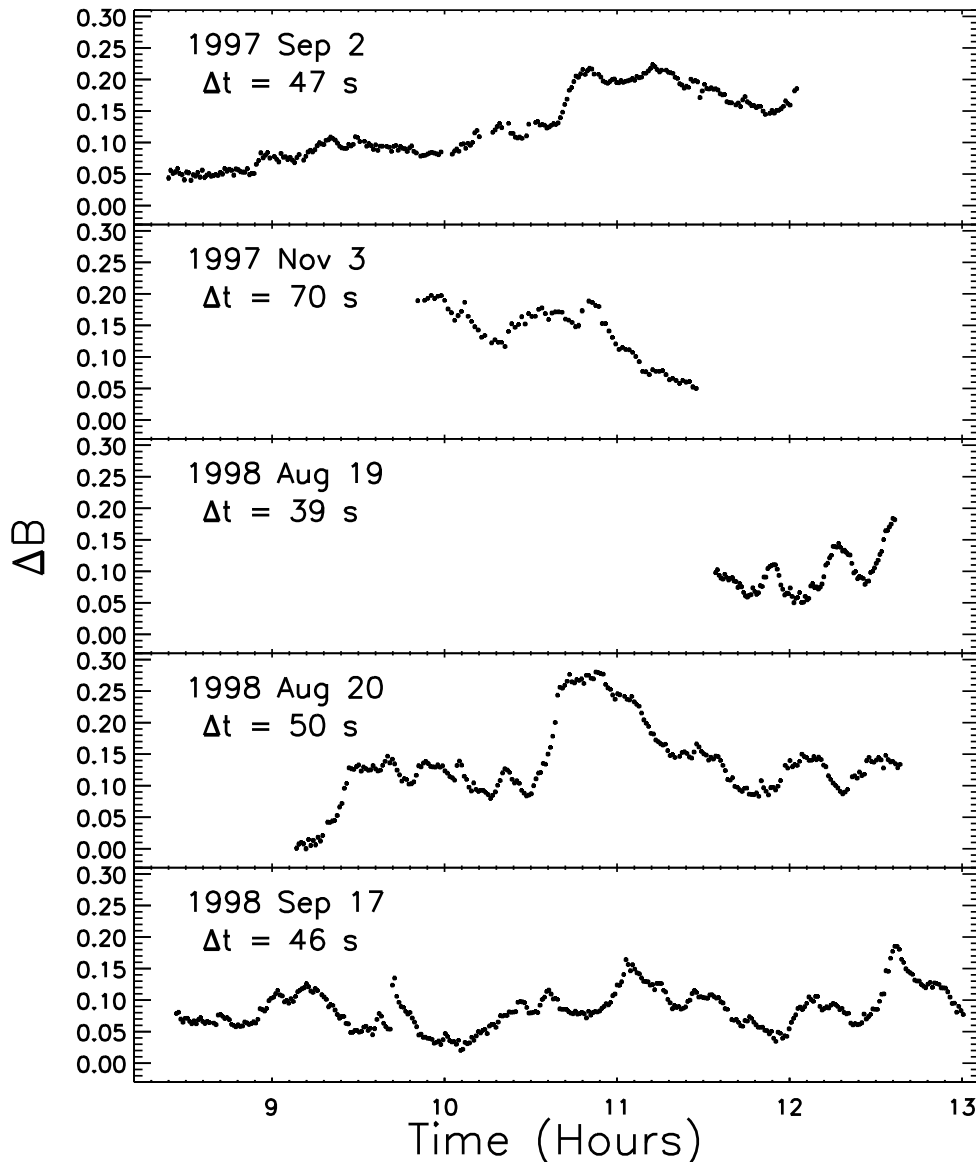


FIG. 2.— Differential B -band light curves for Mira AB. The times between data points for the light curves are $\Delta t = 47, 70, 39, 50$, and 46 s, respectively. The size of the error bars is comparable to that of the point symbols. The time is U.T. on each date.

4. DISCUSSION

The nature of the accreting companion to Mira A may hold the key to improved understanding of mass transfer via a wind, as well as the way in which binaries generate asymmetrical structure in PNe. Whereas early observations of rapid CV-like optical variability by Walker (1957) and Warner (1972) originally led most authors to assume that Mira B was a WD, later revelations that the X-ray luminosity was lower than expected motivated Jura & Helfand (1984) and then Kastner & Soker (2004) to propose that Mira B was instead an accreting MS star. Though Ireland et al. (2007) reported some marginally significant ($4\text{-}\sigma$) features in the optical spectrum that appeared to suggest a MS companion, the UV spectrum is much more indicative of a WD (Reimers & Cassatella 1985). Below, we use a quantitative examination of the amplitude of the optical variability on time scales of

minutes, along with an estimate of the expected optical depth of the accretion-disk boundary layer, to show that the optical to X-ray observations are more consistent with a WD accretor.

4.1. Rapid optical variations and the nature of Mira B

The persistent presence of minute-time-scale stochastic optical variations with the observed amplitude is a strong indicator that Mira B is a WD. Qualitatively, whereas we are not aware of a single example of an accreting MS star with a high time resolution optical light curve resembling those of Mira, most accreting WDs have optical light curves that show Mira-like aperiodic variations with a time scale of minutes — i.e., faster than the dynamical time of a MS star. Quantitatively, the PDS of our Mira light curves have shapes and strengths consistent with those of WDs and not MS stars. The PDS from Mira has a powerlaw index

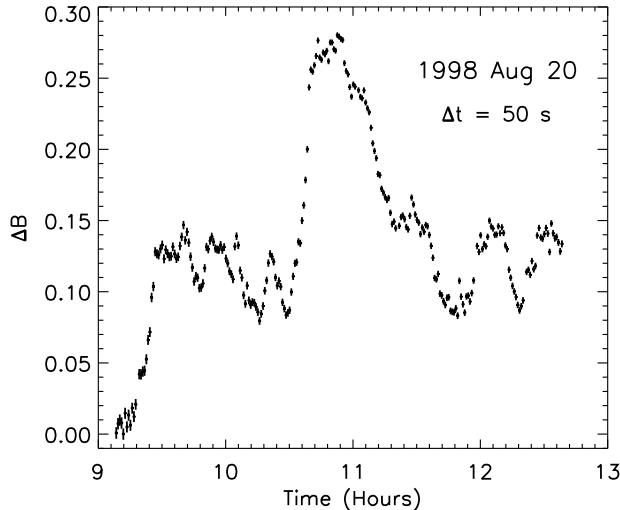


FIG. 3.— Close-up view of the differential B -band light curve for Mira AB on 1998 August 20. The size of the error bars is comparable to that of the point symbols. The time is U.T.

of approximately -2 , like the high-frequency PDS of other accreting objects (including WDs, X-ray binaries, and AGN; e.g., Bruch 1992; Done, Gierliński, & Kubota 2007; Gierliński, Nikolaćuk, & Czerny 2008). We therefore take the rapid variability to be related to accretion. Furthermore, the rms amplitude of the B -band brightness variations from Mira B between 1 and 10 mHz (after accounting for the contribution from the red giant) is around 3% — almost identical to the characteristic value for CVs, which Barros (2008) found to have rms variabilities in the same frequency range of 2.4% in the g' and r' bands and 4.5% in the u' band.

Theoretical considerations suggest that we should not see such rapid variations from a MS accretor. The dynamical and viscous times at the inner edge of an accretion disk around a MS star are ≈ 100 times longer than those at the inner edge of a disk around a WD. Since these are likely the relevant time scales for setting the speed of brightness fluctuations, we expect an accreting MS star to exhibit stochastic variations that are stronger at low frequencies and weaker at high frequencies than the brightness fluctuations from an accreting WD. In fact, light variations have been detected from the accreting MS stars in Algol binaries, and these variations preferentially occur on time scales of days rather than minutes; Olson & Etzel (1995) found variations in the strength of double-peaked $H\alpha$ emission, which they argue trace changes in the inner accretion disk, on time scales of days in a sample of 9 Algol-type binaries. Although we have no empirical constraints on variations from a MS-star disk in the frequency range of 1 – 10 mHz, we expect the amplitude of fluctuations in this frequency range to be orders of magnitude smaller than those from accreting WDs, if, for example, the PDS from an accreting MS star is simply that of a WD but shifted to lower frequencies. Therefore, given that the amplitude of the high-frequency fluctuations from Mira are consistent with those from CVs, and inconsistent with expectations for a MS star, we interpret the accreting object in Mira as a WD.

4.2. Reinterpretation of the X-ray emission

Before addressing the X-ray emission, we use the luminosity of Mira B in the UV and optical to estimate a characteristic accretion rate, \dot{M} , onto Mira B. UV observations with the *IUE* satellite on 1980 June 16 (when Mira A was at pulse minimum and therefore did not contribute to the UV flux) revealed a UV continuum luminosity between 1800 and 3200 Å of $L_{UV} \approx 4 \times 10^{32} (d/107 \text{ pc})^2 \text{ erg s}^{-1}$ (which we estimated from the top panel of Fig. 1 of Reimers & Cassatella 1985). As noted by Reimers & Cassatella (1985), this estimate is a lower limit to the UV luminosity, since an accretion disk could also radiate in the Lyman continuum, which *IUE* would not detect. The *HST* spectra of Mira A and Mira B in Figure 2 of Karovska et al. (1997), taken on 1995 December 11, shows that Mira B produced $L_{opt} \approx 4 \times 10^{32} (d/107 \text{ pc})^2 \text{ erg s}^{-1}$ between roughly 3200 and 5000 Å. Given that Mira B also emits at wavelengths longer than 5000 Å, we estimate that the total, accretion-powered luminosity of Mira B is typically at least $L \approx 10^{33} (d/107 \text{ pc})^2 \text{ erg s}^{-1}$. This luminosity implies that Mira B accretes at a rate of at least $\dot{M}_{WD} \approx 10^{-10} M_{\odot} \text{ yr}^{-1} (L/10^{33} \text{ erg s}^{-1}) (R/10^9 \text{ cm}) (M/0.6 M_{\odot})^{-1}$.

Consistent with our contention that Mira B is a WD, an accreting WD can naturally produce a UV spectrum like the one seen from Mira. The *IUE* spectra from Mira between 1979 and 1983 contained lines with a range of ionization states, including N V 1240 Å, C IV 1550 Å, and Si IV 1400 Å, and line widths — from 135 km s $^{-1}$ for Fe II absorption, to few hundred km s $^{-1}$ for C IV 1550 Å to $\sim 1,000$ km s $^{-1}$ for Ly α and Mg II (Reimers & Cassatella 1985). Moreover, the Ly α profiles that Wood, Karovska, & Raymond (2002) and Wood & Karovska (2004) reconstructed from H $_2$ fluorescence lines observed by *HST/STIS* on 1999 August 2 and by *FUSE* on 2001 November 27 had full widths at half maximum (FWHM) of approximately 1,100 to 1,200 km s $^{-1}$. Velocities of greater than 1,000 km s $^{-1}$ are larger than the fastest Kepler velocities in the vicinity of an accreting MS star, but comparable to the Kepler velocities near an accreting WD. In fact, line widths of $\sim 1,000$ km s $^{-1}$ are often seen in the UV spectra of CVs, which generally emanate from accretion-disk winds (e.g., Mauche 1991; Froning, Long, & Baptista 2003). Furthermore, Reimers & Cassatella (1985) determined that the temperature of the material producing the high-ionization resonance lines in the *IUE* spectrum of Mira (which they take to be the coronal region of the disk) was on the order of 10^5 K — very reasonable for material near an accreting WD.

Regarding the X-ray emission from Mira, an X-ray luminosity that is several orders of magnitude below the optical luminosity from the accretion disk, as we see from Mira B, is exactly what one would expect if the boundary layer (BL) around the accreting WD is optically thick (Patterson & Raymond 1985) or when the spreading layer (SL) on the accreting WD does not extend above the thin disk (Piro & Bildsten 2004). For a slowly rotating WD, roughly half of the energy released via accretion is radiated by the BL (Shakura & Sunyaev 1973; Lynden-Bell & Pringle 1974) or in the latitudinal spreading of the material after it arrives on the WD

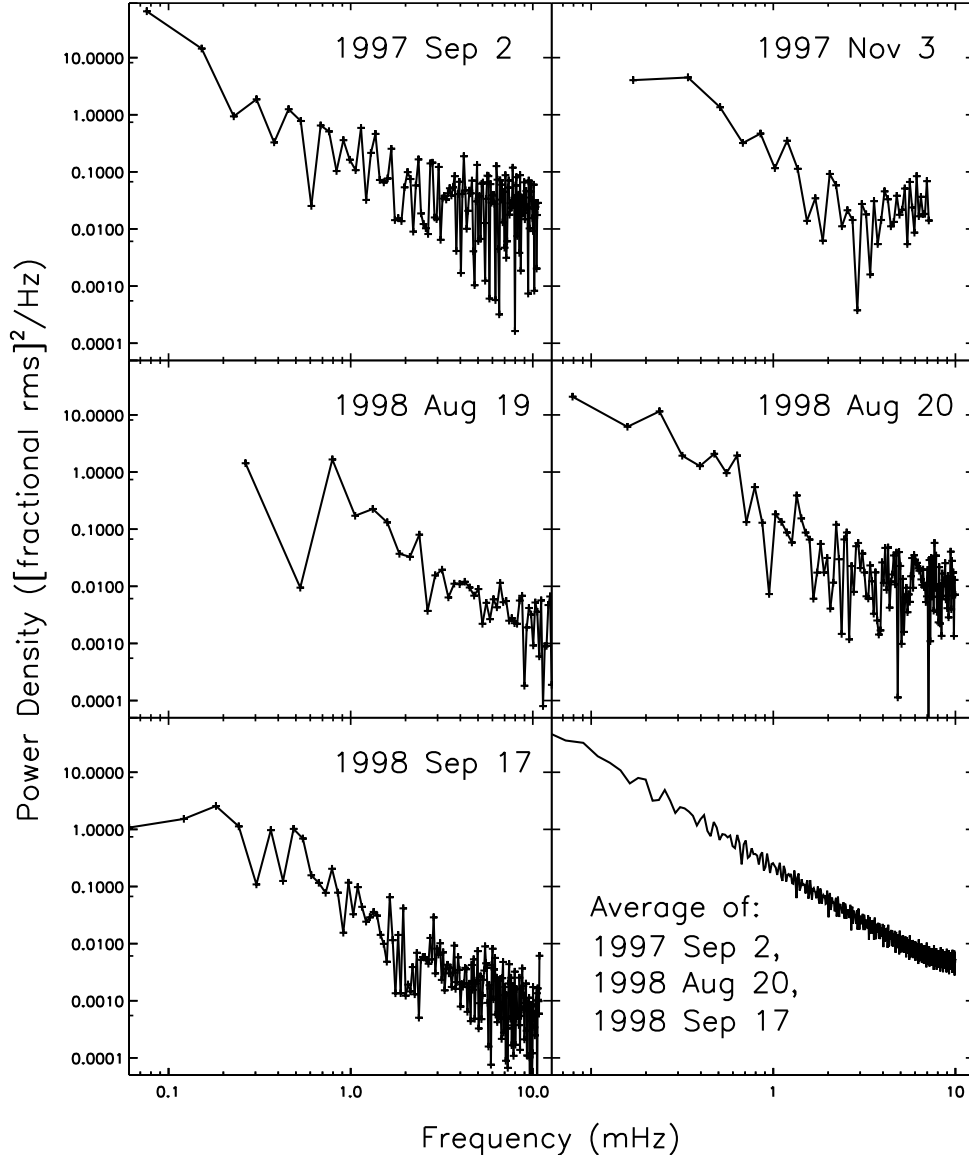


FIG. 4.— Power spectra of the light curves shown in Figure 2. The average PDS in the lower right panel was produced by padding the light curves with enough zeros to generate frequency spacings that were the same for each of the nightly PDS.

(Piro & Bildsten 2004). If the material is shocked as it arrives, the the high Keplerian velocities near the surface of the WD produce hard X-rays that escape if the plasma is optically thin. With an accretion rate of $\dot{M}_{\text{WD}} \sim 10^{-10} M_{\odot} \text{ yr}^{-1}$, we would expect a luminosity of at least a few times $10^{32} \text{ erg s}^{-1}$ from the BL around Mira B. Estimates of the X-ray luminosity, however, all indicate that L_x is no more than a few times $10^{29} \text{ erg s}^{-1}$ (Jura & Helfand 1984; Kastner & Soker 2004; Karovska et al. 2005). Although a detailed investigation of the X-ray emission is beyond the scope of this paper, the low L_x most likely reveals that the boundary (or spreading) layer is optically thick and therefore emitting primarily in the far- or extreme-UV instead of in the X-rays. Wheatley, Mauche, & Mattei (2003) found that for the WD in SS Cygni, the BL became optically thick when the accretion rate rose above $10^{-10} M_{\odot} \text{ yr}^{-1}$,

in accord with our hypothesis that the accretion rate onto Mira B is high enough to quench the X-ray emission. Since the accretion rate at which the BL transitions from optically thin to optically thick increases with WD mass (Popham & Narayan 1995), the optical thickness of the BL around Mira B suggests that the mass of Mira B is lower than that of the WDs in, e.g., the symbiotic binaries T CrB, RT Cru, and SS73 17, which contain WDs with masses greater than $1.0 M_{\odot}$ and BLs that are optically thin at accretion rates as high as a few times $10^{-9} M_{\odot} \text{ yr}^{-1}$ (Luna & Sokoloski 2007; Kennea et al. 2009; Eze, Luna, & Smith 2010).

The existence of other WDs that accrete from the wind of a red giant and produce a very low X-ray luminosity supports our claim that the X-ray luminosity from Mira B is consistent with WD accretion. For example, the accretor in R Aqr, which Jura & Helfand (1984)

also suggested was a MS star based on its low X-ray luminosity, was later shown by *IUE* to have an effective temperature of 61,000 K and the radius of a WD (Meier & Kafatos 1995). More generally, Mürset et al. (1997) found that the bolometric luminosities of the wind-fed WDs in symbiotic stars (such as EG Andromedae, PU Vulpecula, and RX Puppis) often exceed their X-ray luminosities by as much as 5 orders of magnitude.

Finally, a different suggestion for Mira B — that the faint X-rays are coronal emission from a magnetically active, rapidly rotating low-mass MS star (Kastner & Soker 2004) — cannot explain either the strong UV emission (compared to X-rays) or the red-noise-type optical variations. Whereas the luminosity of the rapidly variable component of the optical emission from Mira B is on the order of 10^{32} erg s $^{-1}$, the time-averaged power of optical radiation from stellar flares rarely exceeds 10^{30} erg s $^{-1}$ (Shakhovskaya 1989). More importantly, a MS star producing an X-ray luminosity of a few times 10^{29} erg s $^{-1}$ due to coronal emission would only have a time-averaged optical power from flares of $\sim 10^{29}$ erg s $^{-1}$ (Shakhovskaya 1989). We can thus rule out coronal emission from a magnetically active, rapidly rotating, MS star on energetic grounds. The radio emission from Mira B is also one to three orders of magnitude greater than expected from a magnetically active dwarf (Matthews & Karovska 2006). In contrast, all available observations are consistent with the picture in which a WD is accreting from the wind of the red giant.

5. CONCLUSIONS AND IMPLICATIONS

Our main conclusion is that the rapid optical variability from Mira AB reveals Mira B to be a WD. The amplitude of the optical brightness fluctuations from Mira B on time scales of minutes is the same as those from accreting WDs in CVs, and significantly larger than one would expect from an accreting MS star. The UV spectra — especially the ionization states and widths of the lines — are consistent with the conclusion that Mira B is a WD. The X-ray luminosity and spectrum are also consistent with this conclusion if the accretion-disk boundary layer is optically thick, as one would reasonably expect for our estimated accretion rate of $\sim 10^{-10} M_{\odot}$ yr $^{-1}$ (e.g., see Wheatley, Mauche, & Mattei 2003).

This accretion rate, which we infer from the optical and UV luminosities of Mira B, is consistent with constraints on the effective temperature of the WD from UV spectra. Sion (1999) noted that prolonged accretion will re-heat an otherwise cooling WD, making it potentially visible in the UV or optical continuum. Such rejuvenated WDs are seen in dwarf nova systems during quiescence, revealing effective temperature of $T_{\text{eff}} = 10,000\text{--}20,000$ K (Townesley & Gänsicke 2009). This WD re-heating (Townesley & Bildsten 2003; Townesley & Gänsicke 2009) and the resulting T_{eff} depend on both M and the time-averaged accretion rate, $\langle \dot{M} \rangle$, thereby providing another constraint for our analysis of Mira B. From the UV continuum flux upper limit $F_{\lambda}(1250\text{\AA}) < 10^{-14}$ ergs cm $^{-2}$ s $^{-1}$, Reimers and Casatella (1985) found $T_{\text{eff}} < 14,000$ K for $R = 0.012 R_{\odot}$ (for a WD with $M = 0.6 M_{\odot}$ and a distance of 77 pc; a slightly higher T_{eff} is allowed at our adopted distance of 107 pc). A direct application of Townesley & Bildsten

(2003, see their Figure 1) converts this upper limit on T_{eff} into the long-term accretion rate constraint $\langle \dot{M} \rangle < 2 \times 10^{-10} M_{\odot}$ yr $^{-1}$, in agreement with our earlier estimate.

At this accretion rate ($\dot{M} \approx 10^{-10} M_{\odot}$ yr $^{-1}$), the accumulated matter on the WD will burn unstably and cause a classical novae, leading to the violent ejection of $\sim 10^{-4} M_{\odot}$ of material at > 1000 km s $^{-1}$. This ejected mass is larger than the total mass of the wind between the WD and the red giant, leading to little deceleration of the shock as it plows through the wind in the few months following the eruption. A nova eruption from Mira would thus perhaps look more like those of the symbiotic slow novae than, say, an X-ray bright eruption of the symbiotic recurrent nova RS Ophiuchi (Sokoloski et al. 2006) or the γ -ray producing explosion of the symbiotic V407 Cygni (Abdo et al. 2010). From the work of Townesley & Bildsten (2004), we would expect a nova recurrence time of $\approx 10(2) \times 10^5$ yr for $M = 0.6(1.2) M_{\odot}$ and $\langle \dot{M} \rangle = 2 \times 10^{-10} M_{\odot}$ yr $^{-1}$.

Our conclusion that Mira B is a WD accreting at $\dot{M} \sim 10^{-10} M_{\odot}$ yr $^{-1}$ has implications for the mode and efficiency of mass transfer in wide binaries. Although Mohamed & Podsiadlowski (2007) and de Val-Borro, Karovska, & Sasselov (2009) have suggested that a focused wind could enable up to tens of percent of the donor wind to be captured, the accretion rate needed to produce Mira B's luminosity and effective temperature is just 0.1% of the RG wind mass-loss rate (Ryde et al. 2000). It is also below the Bondi-Hoyle accretion rate of $\dot{M}_{BH} \approx 10^{-8} M_{\odot}$ yr $^{-1} (M/0.6 M_{\odot})^2 (7 \text{ km s}^{-1}/v_{\infty})^3$, where v_{∞} is the relative velocity of the wind at Mira B. Thus we find no evidence that either gravitational focusing or wind Roche-lobe overflow is enhancing the accretion efficiency onto the WD in this binary, despite the image showing a bridge of X-ray emitting material between the two stars (Karovska et al. 2005).

Identifying Mira B as a WD also has ramifications for the launch site of the bipolar “streams” that have been imaged in the near- and far-UV with *Galex* (Martin et al. 2007) and in the optical from the ground (Meaburn et al. 2009). Based on the behavior of other WDs that accrete from wind-fed disks in symbiotic binaries, we speculate that the the bipolar streams emanate from the accreting WD rather than, or in addition to, the pulsating AGB star. Mikołajewska (2003) has suggested that symbiotic stars in which the wind of the red giant is focused toward orbital plane — as has been seen to be the case for Mira (Karovska et al. 2005) — preferentially contain large, unstable accretion disks, which tend to produce sporadic bipolar outflows (Sokoloski 2003). *Galex* observations indicate that the streams from Mira contain about $10^{-7} M_{\odot}$ of material (Don Neill, private communication), and Meaburn et al. (2009) estimated that the streams were ejected over the course of the past $\sim 1,000$ yr. The average rate of flow into the streams was thus roughly $\langle \dot{M}_{\text{streams}} \rangle \sim 10^{-10} M_{\odot}$ yr $^{-1}$. Given our estimate of the accretion rate, Mira B could fairly easily pump $\sim 10^{-11} M_{\odot}$ yr $^{-1}$ into the streams, which is roughly consistent with the observational estimate of the mass-loss from the WD by Wood, Karovska, & Raymond

(2002) during the *IUE* era. Given the large uncertainties on both the rate of accretion onto Mira B, the average rate of mass loss from Mira B, and the rate of flow in the bipolar streams, we conclude that the WD remains a viable the launch site, and that the streams do not *necessarily* originate from the RG. Mira AB therefore does not necessarily require a mechanism for generating fast, bipolar outflows from the AGB star itself, and it does not provide evidence that such mechanisms are needed to generate bipolar symmetry in PNe.

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